The use of LS-DYNA to Assess the Performance of Airborne Systems North America Candidate ATPS Main Parachutes

Benjamin A. Tutt[*] and Anthony P. Taylor.[†]
Irvin Aerospace Inc, Santa Ana, CA, 92704

Jean-Christophe Berland[‡]
Para-Flite Inc, Pennsuaken, NJ, 08109

and

Bill Gargano[§]
Quantum Parachutes LLC, Boulder, CO, 80304

The Finite Element Analysis (FEA) tool LS-DYNA has been used to assess the performance of two Advanced Tactical Parachute System (ATPS) main parachute candidates proposed by the North American Division of the Airborne Systems Group. This paper presents the use of an Eulerian-Lagrangian penalty coupling algorithm and multi-material ALE capabilities within LS-DYNA to replicate the quasi-steady-state characteristics of the MTR1-C and the Irvin "Model C" parachutes. This class of simulation is often referred to as a Fluid Structure Interaction, or simply FSI, model. An FSI model combines a structural or Lagrangian mesh with a Navier-Stokes based Eulerian fluid domain. The methodology described in the paper permits analysis of each parachute in an infinite mass (wind tunnel type) environment. This approach involves constraining the payload or confluence and applying a prescribed airflow to the constructed parachute geometry. By adopting this method, the computationally intensive inflation phase can be omitted and the quasi-steady-state post inflation behavior can be captured. Although the original motivation of this study was to replicate parachute testing, the accuracy and insight obtained from early simulations resulted in the use of these techniques to both reinforce and guide design development. While these may be the first examples of applying FSI class simulations as a driver in the design and development of parachutes, the benefits of the tool to this program remain inescapable. At the very least, the ability to visualize the flying shape of a newly designed parachute prior to fabrication or testing is an advanced technology that will aid the parachute designer. The ability to anticipate the aerodynamics throughout the canopy and to understand the associated effects of the airflow on the parachute performance have proven to be invaluable tools in the parachute development process. A discussion of the merits of this approach, its current limitations, computational requirements and applicable future code enhancements is also included.

Nomenclature

C_d	=	drag coefficient
F	=	force
s	=	area
q	=	dynamic pressure
psia	=	pounds per square inch (absolute)

---

[*] Systems Analyst, Analysis Dept.
[†] Director Business and Technical Development.
[‡] Chief Engineer.
[§] Designer.

I. Introduction

THE Advanced Tactical Parachute System (ATPS) will serve as a replacement for the T-10 tactical mass assault troop parachute system. The T-10 parachute was designed to deliver a gross weight of 250 lb, while the weight growth of modern combat-ready soldiers has reached almost 400 lb. This significant increase in parachute payload weight can be attributed to a combination of larger soldiers and associated equipment. The rate of descent of a modern day soldier using a T-10D parachute can range from 20-26 ft/s, a significant amount of energy that needs to be dissipated through the ankles and knees of the jumper during ground impact. Not surprisingly, this has lead to an increase in landing related injuries. The T-10 parachute has been modified a number of times to counteract this increase in delivery weight but has now reached the limits of its growth and a replacement with higher payload capacity is urgently required.

This paper documents the efforts undertaken by Irvin Aerospace Inc. (Irvin) to assess the capability of current simulation resources to analyze the performance of two Airborne Systems North America ATPS main parachute candidates, the Para-Flite MTR1-C and the Irvin "Model C".

The ATPS program has allowed parachute simulation techniques to be assessed in conjunction with an ongoing parachute design and testing activity. This real-time assessment has assisted in identifying design advantages and disadvantages of current analysis techniques.

This paper presents a methodology applicable to steady descent phase analysis of parachutes. This strategy is then demonstrated for the two parachutes described above. Finally, the current limitations of both software and hardware are discussed, and future enhancements that are expected to address these restrictions are considered.

II. Simulation Definition and Background

The performance characteristics of a parachute can be traced back to complex interactions between the parachute structure and the fluid through which it flows. The combination of bluff body aerodynamics and a highly deformable structure, fabricated from a porous media, creates a truly unique and multifaceted design environment.

Irvin has utilized the transient dynamic finite element program LS-DYNA[1] for over 8 years for the analysis of fabric structures, including impact attenuation airbags, protective nets and other static fabric assemblies. Irvin has developed a high level of confidence in the accuracy of LS-DYNA predictions and routinely utilizes a finite element analysis process in the design of its engineering products. This has resulted in reduced testing requirements and more efficient solutions for a number of parachute subsystem components, but its influence had stopped there, at the component level.

Over the past 4 years Irvin has investigated the capability within LS-DYNA to simulate the elaborate connections between a structure and associated flow field.[2] Within the past two and a half years, the combination of code improvements and the availability of suitable computing resources, has highlighted the potential of this solver for predicting parachute performance.[3]

A multitude of finite element analysis techniques have been developed and employed to simulate various functions of a parachute system. These techniques can be separated into the following three approaches:

A. Computational Structural Dynamics

This class of analysis involves applying distributed loading to a given parachute geometry. The more complex structural analysis methods apply a time dependent loading that approximates the inflation process. These techniques produce valuable results when the canopy in question is historically well characterized. The canopy loading inputs rely upon wind tunnel test results or computational fluid dynamic outputs. For this reason, its applicability is reduced when considering new designs or new flight regimes for existing canopies.

B. Computational Fluid Dynamics

Some insight into parachute aerodynamics can be gained from CFD analysis of flow around a rigid body that approximates the instantaneous geometry of a parachute in flight. However, the inherent instabilities associated with bluff body aerodynamics suggest that this technique has limited applicability when characterizing the performance of a parachute. The presence of re-circulation and the accompanied reverse flow in the wake of the bluff body indicate the potential of such flow conditions to create asymmetric instabilities. It is a well-accepted and routinely observed phenomenon that a flat circular parachute experiences such asymmetric fluctuations. To summarize, CFD analysis can be a valuable tool but the time-dependent nature of parachute flight and the inability of CFD to account for changes in the parachute geometry due to its surrounding flow field limits its relevance.

C. Fluid Structure Interaction

In general terms, FSI techniques involve the coupling of structural and fluid dynamics. The methods utilized to achieve this coupling are dependent upon the programs used and to some extent the analysis application.

One approach used to couple the two techniques is to employ separate structural and fluid solvers. This has the benefit of incorporating codes that are enhanced for their specific discipline, either structural or fluid analyses. Typically, these techniques revert to an implicit time-integration method to transfer the effects of one solver to the other. Displacements in the structural output act as boundary conditions for the fluid solver, consequently, this requires the fluid domain to be rezoned or remeshed each time data is transferred from code to code. Automated mesh moving algorithms have been generated which allow the accurate representation of the fluid structure interface, however, these steps can become computationally intensive and at times, can lead to inconsistent mesh quality.

An alternative approach is to perform both the structural and fluid computations with the same code. The obvious benefit of this scheme is that no inter-code data transfer is necessary. Logically, this approach could contain highly developed structural algorithms and a less mature fluid counterpart, or vice versa.

The combined structural and fluid solver method has been used for the work presented in this paper and is covered in more detail in the following section.

III. Simulation Methodology

It is possible to use LS-DYNA in a number of ways to simulate this highly dynamic, fluid and structural event. Numerical instabilities due to element distortions limit the applicability of using only a Lagrangian formulation, for both the parachute and the flow field, when modeling the large deformations associated with parachute behavior. The Lagrangian description remains a viable option for the structure. An alternative technique for the fluid domain is a multi-material Eulerian formulation. This formulation permits material flow through a mesh, fixed in space, whose elements are allowed to contain a mixture of different materials. This method completely avoids any mesh distortions for the fluid domain. The incorporation of an Eulerian-Lagrangian penalty coupling algorithm permits the interaction of Eulerian and Lagrangian parts within the same simulation.

The Eulerian formulation is not completely free from shortcomings. The user must be aware of the propensity for dissipation and dispersion inaccuracies connected with the fluxing of mass across element boundaries. In addition, the Eulerian mesh is required to span the entire range of activity associated with the Lagrangian structure. In many applications, this can surmount to a large size mesh and hence a high computing cost. To circumvent these possible weaknesses the following methodology has been applied for this body of work.

1. *Model the parachute using a Lagrangian formulation.*
2. *Model the fluid domain using a Navier-Stokes based multi-material Eulerian formulation.*
3. *Perform the analyses using conditions similar to a wind tunnel, i.e. infinite mass; equating the results to the quasi-steady-descent phase of the parachute use.*

This 3 step approach reduces the computing cost that would be required to capture vast spatial timelines associated with real parachute functions. It also permits the reduction in complexity of boundary conditions. The use of a penalty-based coupling algorithm significantly reduces the energy conservation errors connected with alternative constraint-based techniques. Kinetic energy is consumed at interfaces when constraint-based coupling methods are used, this is inappropriate when considering a parachute simulation. Primarily, this approach was conceived because it creates an environment in which the FSI technique can be assessed.

IV. Parachute Analyses

A. Para-Flite MTR1-C and XT-11

The Para-Flite MTR1-C, as shown in Fig. 1, has evolved from a previous ATPS main parachute candidate, the XT-11. The primary design modification is the incorporation of a slot along each of the arms. This feature is discussed below.

During initial stages of this work it became apparent that the technique could be used to more fully understand the flight characteristics of the XT-11 and provide a level of comparison with MTR1-C performance. The simulation approach described in Section III was implemented for both canopies. In order for the parachutes to achieve a flying shape the model is initiated with the parachute in a "constructed" configuration and fluid flow is used to "inflate" the parachute. This quasi inflation process was by no means an attempt to replicate the true inflation of the parachute. It was used purely to reach a steady descent phase with the correct parachute geometry. For the purpose of this work the analysis begins after the effects of the quasi inflation have subsided.

Figure 1. Para-Flite MTR1-C.

Figure 2 displays the fluid domain and the structural mesh used to model the parachute. The fluid domain is constructed in such a manner that a continuous source of air, at a controllable velocity, flows from the bottom of the mesh and exits at the top, much the same way as it would in a wind tunnel. For these analyses, the velocity and pressure of the inflow air remained constant at 18 ft/s and 14.7 psia, respectively.

The models were constructed using HyperMesh, a member of the HyperWorks Suite developed by Altair Engineering, and executed using LS-DYNA version 970, revision 3535, running on a 3 GHz, 32-bit PC workstation. Post-processing activities were performed using HyperView, another member of the HyperWorks Suite, and EnSight version 8.0, developed by CEI. EnSight was primarily used to view the parachute in the flow field while HyperView enabled the monitoring of model performance and evaluation of time history ASCII files.

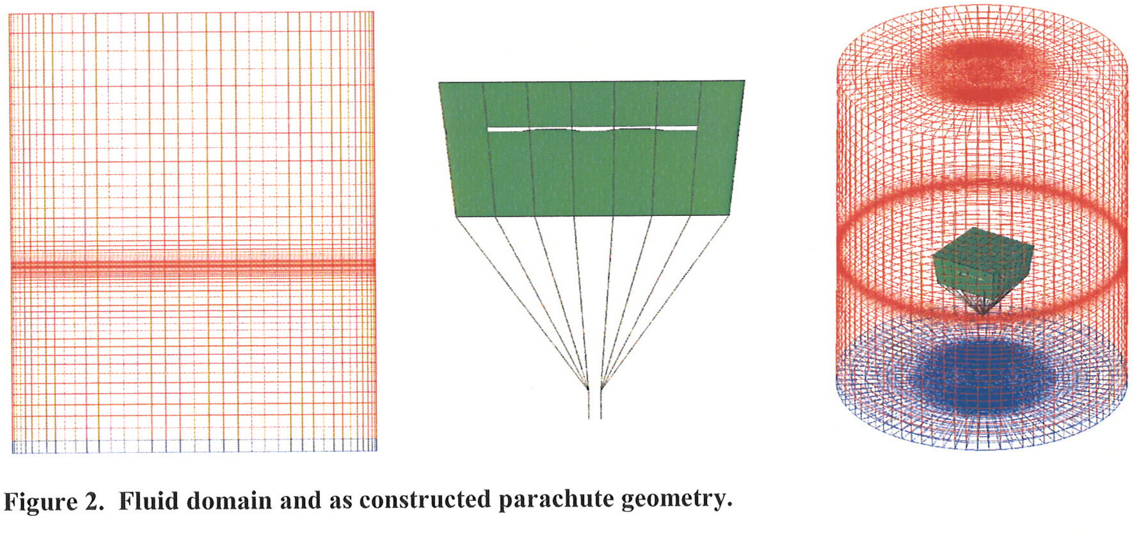

Figure 2. Fluid domain and as constructed parachute geometry.

As can be seen in Fig. 2, the simulated geometry does not include the slider, which is used to control the inflation of both the XT-11 and the MTR1-C. Both designs include 4 risers that meet at 2 points- the shoulders of the jumper. For analysis purposes these 2 points are constrained in all degrees of freedom.


Figure 3. Comparison of predicted and observed XT-11 inflated shape.

Figure 3 illustrates the predicted XT-11 inflated geometry and that which is observed during test flights. The figure acts as a strong qualitative comparison of the two shapes. This simulation was extended beyond the state shown in Fig. 3. The resulting motion of the parachute further highlighted the potential of this technique. As the parachute reached its flying shape the canopy began to fall to one side.

An additional simulation was conducted that removed the constraints of the payload that limited motion along the horizontal plane. By removing these constraints, motion of the payload (in one plane) as it reacted to the movement of the canopy and the subsequent closed-loop effect that this had could be captured.

As the constraints were removed, the parachute started to travel in a circular pattern. This motion was truncated due to the size of the fluid domain; as the parachute moved towards the boundary the accuracy of its motion deteriorated. This initial motion appeared to replicate that observed in recent flight tests of the parachute. Due to the necessary computing requirements the option of simply enlarging the fluid mesh was not feasible. A compromise was to use an Arbitrary-Lagrangian-Eulerian (ALE) function within LS-DYNA that allows the fluid mesh to track the Lagrangian mesh. The use of this method is not ideally suited to this application, and inaccuracies that this introduced into the model, meant that no quantitative analysis could be gained. It was, however, intriguing to see the resulting motion. The parachute repeated the movement observed when placed in the fixed mesh and additionally, at times came to a halt or moved off in another direction. This secondary motion also correlated well with flight tests. Again, it is important to note that although interesting, this extended motion, utilizing mesh-moving techniques, could have been a reaction to boundary conditions.

Figure 4. Velocity vectors on a section plane through the XT-11.

The next step was to determine if the model could be used to help explain this flight characteristic. The use of Ensight to observe the dynamics of the fluid flow proved beneficial to understanding this motion.

Figure 4 illustrates the velocity profile of the air surrounding the parachute at the instant it began to fall to one side. It is important to note that the direction of this initial motion was not towards a vent or towards the center of an arm but followed a course between the two. The image illustrates velocity vectors on a section through opposing corner vents. These vectors are scaled and colored in accordance with the velocity of the air at the base of the vector. The curved arrows simulate the direction taken by massless particles inserted into the flow field at the base of the vector.

Another interesting flow feature is the location and distribution of vortex cores. Figure 5 displays the vortex cores associated with the velocity vectors shown in Fig. 4.

The relative difference in volume and strength of vortex cores between the left and right of the canopy, as shown in Fig. 5, facilitates the movement of the canopy from a high to a low-pressure environment. Figure 5 also shows a vortex ring shed from the canopy during the quasi inflation phase.

By creating a design that generates a consistent pattern of shed vortices around the canopy, the likelihood of a steady pressure distribution across the canopy is increased.

The design of the MTR1-C enables a more uniform pattern of vortices to be shed from the skirt of the canopy. The inclusion of slots in the canopy fabric along each arm creates an exiting flow that disturbs the vortices created at the skirt before any non-uniformity can affect its performance. Figure 6 presents a composite image of velocity vectors and vortex cores associated with the MTR1-C. The left side of the image displays velocity vectors and the right side shows the associated vortex cores. It is noticeable that flow can be seen exiting the canopy through the slots in the arms. The flow rate of air exiting the canopy is somewhat less than expected. This was thought to be due to a lack of fluid elements across the slots as apposed to a deficiency in the modeling methodology. An additional simulation, which included slots double the height of the originals, was conducted to verify this condition. The results indicated that having more fluid elements across the feature allowed more fluid to pass through. From these results, it can be inferred that if smaller elements were to be placed around the original size slots, the flow could be better resolved. Existing computational resources rendered the run-time associated with a reduced time-step (smaller elements) infeasible.

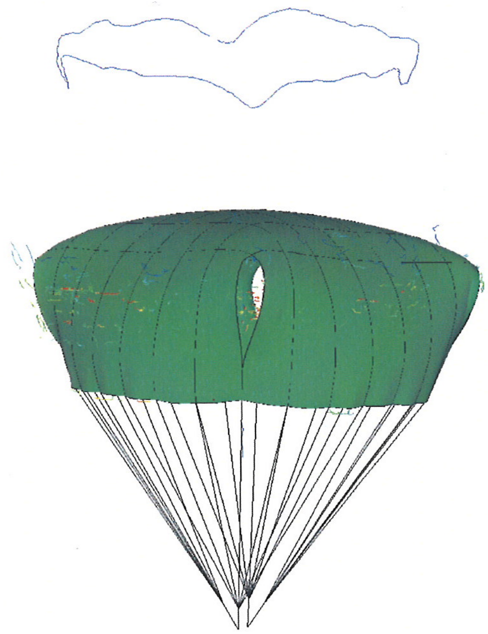

Figure 5. Location of vortex cores in the XT-11 flow field.

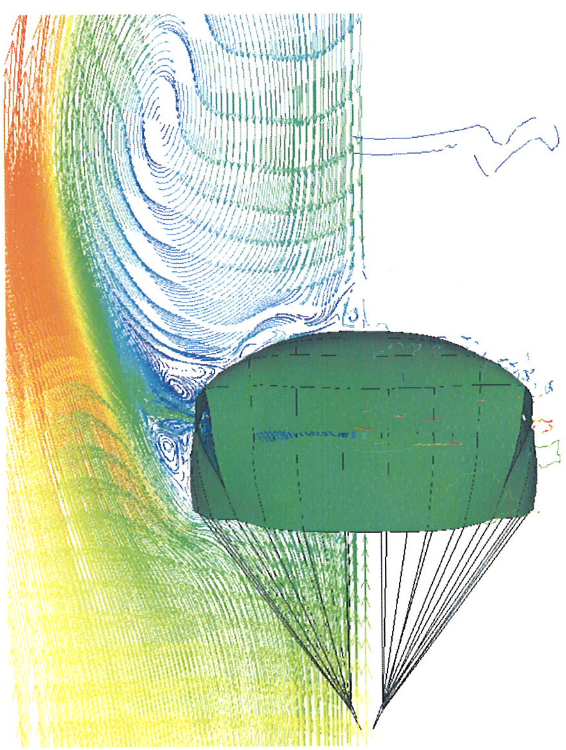

Figure 6. Composite image of velocity vectors and vortex cores for the MTR1-C.

Clearly, these simulations have the capability of providing a great deal of information to the user. An interesting feature is the ability to extract the force generated in the suspension lines and risers. Knowledge of the flow velocity and pressure combined with the force in the risers, enables a drag coefficient, C_d, to be calculated. Figure 7 displays time history data of the riser angles for each of the 4 risers. Utilizing the angle of the risers and Eq. (1) a drag coefficient, within 3% of measured test data, was predicted.

$$C_d = \frac{F}{s \cdot q} \quad (1)$$

B. Irvin Model C

The Irvin Model C represents a proposed Irvin ATPS main parachute design iteration. The decision to model this parachute was taken following the benefits observed during the simulation of the XT-11 and MTR1-C.

The Irvin Model C is a 28 gore, extended skirt parachute that contains two circumferential slots, and radial gaps between adjacent gores. The presence of a large number of small slots and gaps make the design considerably more challenging to simulate. The generation of the fluid mesh becomes particularly important, as the placement of fluid elements around these features will affect predicted performance.

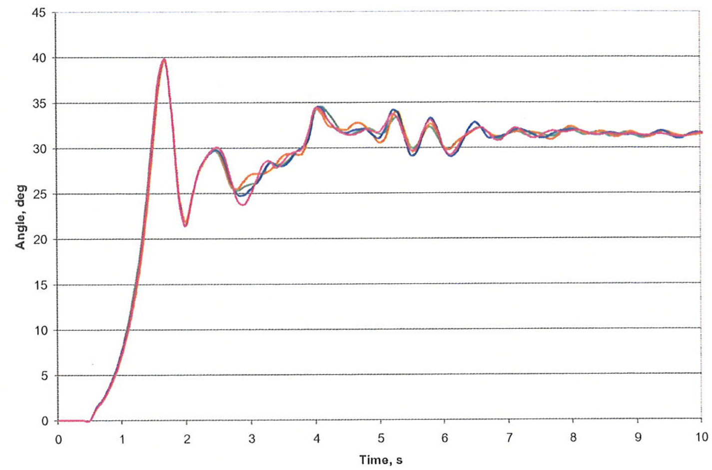

Figure 7. Riser angle time history data for the MTR1-C.

The simulation methodology described in Section III was implemented for this parachute. The velocity and pressure of the inflowing air was 18 ft/s and 14.7 psia, respectively. A comparison of the predicted and test observed inflated shapes is presented in Fig. 8. Again, the similarity of the two images is encouraging. The model appears to accurately replicate the taut radials and skirt band, and the associated flaccid cloth.

It can be seen from Fig. 8 that the higher, narrower of the two circumferential slots was omitted from the simulation. This was a direct consequence of the size and quantity of fluid elements required to accurately simulate such a feature. In the same way that smaller and additional fluid elements would benefit the MTR1-C simulation, the ability to use more fluid elements would enable this feature of the Model C to be simulated.

The Irvin Model C parachute contains two different forms of netting: netting that spans the features discussed above in addition to an anti-inversion netting at the skirt of the canopy. This highly porous media is not included in the model.

Currently, there are no suitable means of including fabric permeability, a subject considered in the following section.

Figure 9 illustrates velocity vectors on a section through the canopy aligned with two of the

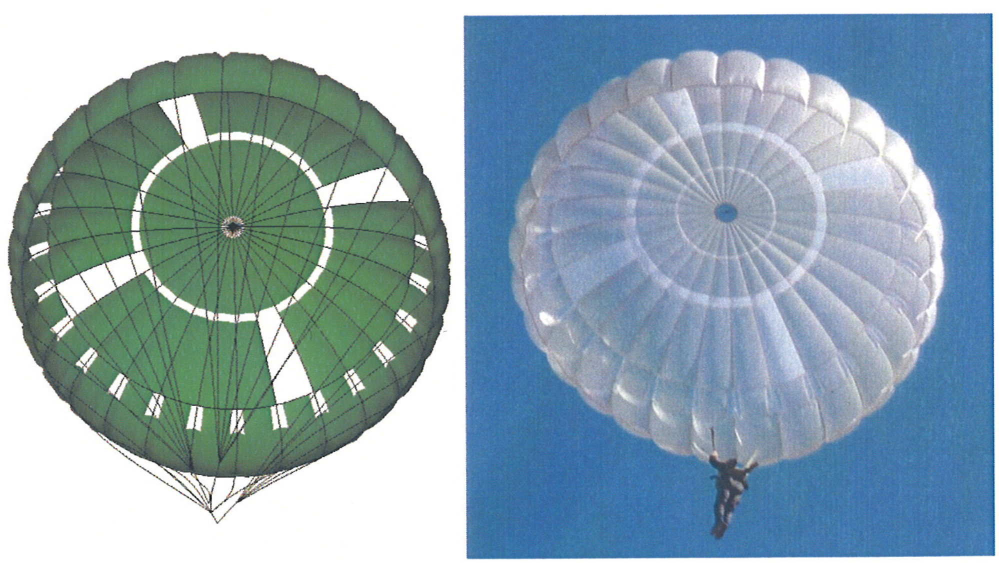

Figure 8. Comparison of predicted and observed inflated shape of the Irvin Model C.

large mesh sections. This image really helps to visualize the quantity of air escaping through these large mesh sections and the effect this flow has on the wake of the parachute. It is encouraging to see the model predicting an increase in velocity of the air as it passes through the features in the canopy. Another useful product of this type of simulation is the ability to visualize and quantify the stress experienced by the parachute components during this phase of flight. For the Irvin Model C, and similar parachutes, the peak stress or load will occur during inflation, however, for other parachute applications this may not be as unambiguous.

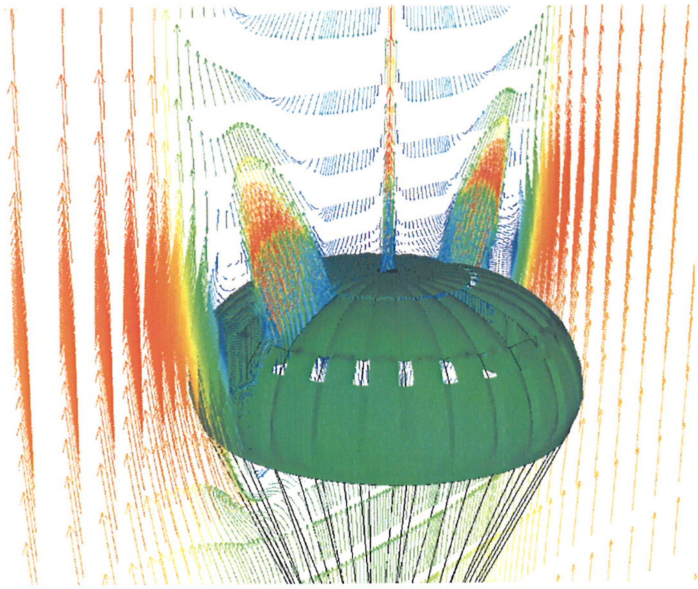

Figure 9. Velocity vectors on a section plane through the Irvin Model C.

V. Current Limitations and Future Enhancements

Perhaps the most significant limitation of the parachute simulation technique described within this paper is the inability to integrate fabric permeability. It has been well documented that parachute porosity can have a considerable impact upon parachute performance. Parachute drag, stability and opening forces are all influenced by the total porosity of a parachute canopy. An assumption of zero porosity is valid for the parachutes considered during this study, they are constructed from a low porosity fabric. Although it has been shown that geometric porosity can be assessed with this approach, a reliable method to evaluate fabric permeability is still required. Efforts are ongoing between Irvin and developers to incorporate a suitable technique, current plans include algorithm testing in summer 2005.

An additional limitation of the modeling technique is the lack of coupling between the risers/suspension lines and the fluid. Although this deficiency would not have a substantial affect on the ATPS candidates discussed in this study, as dynamic pressure and number of suspension lines increases this will become more important. It should be noted that methods are available for incorporating line-induced drag in the simulations. However, the computational resources required to evaluate such methods have left the technique unproven.

As discussed throughout this paper, computational resources are a prime driver in the quality and accuracy of the results gathered from the simulations. The number of fluid elements required in a simulation to accurately capture the flow of air through slots and vents increases substantially as the size of the slot or vent reduces. The Para-Flite XT-11 proved a great model to initiate this study, it had few slots and gaps and so required relatively few elements. As the study progressed and the Irvin Model C was evaluated the requirement for fluid elements grew rapidly. If ribbon or ringsail parachutes were to be considered this need for fluid elements would grow almost exponentially. The Irvin Model C simulation consisted of 300,000 fluid elements and required 5 days to achieve a suitable state. This is clearly not conducive to evaluating numerous design modifications and application permutations. If this method is going to become an inherent part of parachute design processes then simulations consisting of 5 million elements will have to be evaluated within an acceptable time period.

The extension of this methodology to a finite-mass-type simulation is believed to be solely reliant upon computational resources.

Additional work undertaken at Irvin to evaluate a similar methodology to assess the ability of LS-DYNA to replicate inflation characteristics has also been published.

VI. Conclusion

Parachute behavior is a complex interaction of parachute and flow field. To appropriately simulate this behavior a means of assessing the relationship is required. Analysis of a parachute or a flow field without its associated partner is excluding the inherent interaction between the two.

This paper presents a method for conducting FSI simulations using the commercially available transient dynamic finite element analysis program LS-DYNA. The methodology has been assessed in parallel with the Advanced Tactical Parachute System main parachute development effort.

These may be the first examples of applying FSI class simulations as a driver of the design and development of parachutes. The benefits of utilizing this simulation technique for the design of the two parachutes are indisputable. The ability to visualize the flying shape of a newly designed parachute prior to fabrication or testing is of significant value to a parachute designer. The ability to anticipate the aerodynamics throughout the canopy and to understand the associated effects of the airflow on the parachute performance are proving to be invaluable tools in the parachute development process.

The accuracy of the results has also been encouraging; the ability to replicate the motion observed in flight tests of the XT-11 and the subsequent elimination of this motion with the MTR1-C was not anticipated. Although these could be termed qualitative or anecdotal comparisons, the additional quantitative comparison provided by solid drag coefficient numbers further reinforces the methodology.

In many aspects, the limitations of this approach appear purely computational. The ability to include more fluid elements in the model should allow ribbon and ringsail parachutes to be assessed. Parachute clusters could also be evaluated. Response to user controls could, in theory, also be reviewed and measured.

The inability to consider fabric permeability remains an authentic limitation and will restrict the use of this technique for a number of applications until a suitable solution can be developed.

References

[1]Hallquist, J. O., "LS-DYNA Theoretical Manual," Livermore Software Technology Corporation, 1998.

[2]Tutt, B. A., and Taylor, A. P., "The use of LS-DYNA to Simulate Water Entry Characteristics of Space Vehicles," 8th International LS-DYNA User's Conference, 2004.

[3]Taylor, A. P., "An Investigation of the Apparent Mass of Parachutes under Post Inflation Dynamic Loading through the use of Fluid Structure Interaction Simulations," 17th AIAA Aerodynamic Decelerator Systems Conference, 2003.